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Fire behavior of steel and partially encased composite columns embedded on walls

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ABSTRACT

This paper presents the results of an experimental research on steel and composite partially encased steel columns embedded on brick walls and subjected to fire. The specimens were made of HEA 100 and HEA 220 steel profiles, with the web parallel and orthogonal to the wall's surface. The thickness of the tested walls was 7, 11, and 15 cm depending on the steel profile used in the column. Due to the generated thermal gradient, this type of columns experienced thermal bowing, bending first towards the exposed side and then to the opposite side of the fire. When the column's web is parallel to the wall's surface, a less pronounced thermal gradient is developed, and the column behaves more like to a uniform heated one. The axial restraining forces increasing and after reaching the peak value decreasing quite suddenly. When the column's web is orthogonal to the wall's surface, the steel flange is directly exposed to fire, resulting on its rapid thermal elongation accompanied by a rapid degradation of the mechanical properties of the materials, while the remaining cross-section heats slower. The restraining forces after reaching a peak value descended a little bit and then increasing again up to second peak value, thus part of the cross-section is slowly heating and elongating. The thickness of the brick wall influenced the stiffness of the tested columns, affecting the development of the restraining forces and displacements.

1. Introduction

The building columns are usually embedded on walls and, in a fire situation, they develop thermal gradients along the cross section leading to a phenomenon called thermal bowing. The temperature distribution in the cross-section, which depends on the orientation of the web of the steel profile in relation to the wall's surface, induces additional bending moments and stresses, leading to an early yielding of parts of the cross section. Those effects lead to a reduction on the fire resistance of the columns, especially because these elements are strongly influenced by second-order effects. On the other hand, the fact that the columns are exposed to fire, at only one or three sides maximum, results in a benefit to the columns as it reduces the heating.

One of the reference works in the area was carried out, in 2007, by Garlock and Quiel [1]. The authors performed a numerical study in unevenly heated columns. They have described that in early stages of heating, columns presented a positive bending moment, due to the rotational restraint at the ends, so that the hotter side becomes compressed. At the same time, the effective centroid of the cross-section moves towards the colder side, due to non-uniform distribution of the modulus of elasticity resulting from the thermal gradients. The axial force, applied at the geometric centroid of the cross-section, will now produce a bending moment, since its application point is no longer coincident with the stiffness center of the cross-section. This moment is opposite to the one originated by the rotational restraint, and eventually will surpass the same, leading to a reversal of the resultant moment. It is important to highlight that the thermal gradients produce higher bending moments if they are around the strong axis of the column's cross-section.

Thermal bowing in columns has been studied by the scientific community since the end of the 80s. Cooke et al. [2] carried out experimental and numerical tests on I cross-section columns. The authors presented some advices on how to minimize the thermal bowing effects, such as, choosing materials with low thermal elongation coefficient, reducing the thermal gradients in the cross section and increasing the distance between the exposed and non-exposed sides of the column.

Some authors reported that either beams or columns exposed to thermal gradients and with restraint to thermal elongation presents a similar behavior, which is a combination of axial forces and bending moments, and due to this fact they call these elements as beam-columns (Quiel et al. [3] and Dwaikat et al. [4]). They have tested steel columns with different coating configurations creating specific thermal gradients along the two main axis of the cross-section. The columns presented failure as a result of the combination of axial force and bending moments.

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Agarwal et al. [5] presented a set of numerical studies on steel columns with different heating patterns, some cases similar to those considered in the study of Dwaikat et al. [4]. The numerical model, calibrated with the experimental data, was used to develop a parametric study that analyzed columns with different slenderness and load ratios. The results showed that uniformly heated columns reached in many cases the critical temperature before the differentially heated ones. Regarding the failure modes, the columns with thermal gradients along the flanges presented global buckling around the weak axis. However, the columns with thermal gradients along the web have failed by global buckling around the strong axis or flexural torsional buckling around the weak axis, this last occurred mostly in the slender columns. The paper also presented a simplified calculation method to assess the load bearing capacity of steel beam-columns in fire.

Regarding the current fire design codes, the EN 1994-1.2 [6] presents methods to assess the fire resistance of steel and composite partially encased steel columns fully engulfed in fire, however nothing is foreseen for columns embedded on walls. To overcome this lack, Quiel et al. [3] presented a calculation method for beam-columns subjected to combined axial load and bending moment.

If the number of numeric research works on the topic is small the ones of experimental nature are very scarce. Correia et al. [7–10] conducted an experimental investigation on unloaded steel and composite partially encased steel columns embedded on walls. The influence of the wall's thickness and orientation of the steel profile in relation to the wall's surface were studied. These experimental tests validated a numerical model developed with the Supertempcalc software and, after a large parametric study, new formulas for calculating the temperatures on sections embedded on walls were proposed. Correia et al. [10] have also emphasized that the failure mode of columns embedded on walls is very different from the isolated ones. It was verified that failure is not abrupt and occurs by bending.

It is also known that steel and composite steel and concrete structures subjected to fire need quite always fire protective materials for preventing the rapid degradation of the mechanical properties of the materials with the temperature. The structure can be with this saved from collapse in case of fire (Faggiano et al. [11]).

Rodrigues et al. [12], in 2015, have also evaluated the influence of the concrete encasement on the thermo-structural behavior of totally encased composite columns subjected to fire. The authors have found that the concrete encasement increases considerably the fire resistance of the column without requiring any additional thermal insulation.

Considering the same philosophy of the studies presented by Correia et al. [7–9], this paper presents a new series of fire resistance tests on steel and composite partially encased steel columns embedded on walls but in this case with restraining to thermal elongation. These tests are different from the previous, because beyond the restraining to thermal elongation, the columns were subjected to a serviceability load during the heating process. Also, as they have been tested composite partially encased steel columns the effect of the concrete encasement in the behavior of these columns embedded on walls and subjected to fire was also tested. The tests were carried out at the Laboratory of Testing Materials and Structures of Coimbra University, in Portugal.

2. Experimental tests

2.1. Test set-up

In Fig. 1 are presented the test set-ups developed at Coimbra University for fire resistance tests on building columns with restrained thermal elongation. In Fig. 1a for columns embedded on walls and in Fig. 1b for isolated columns. The explanation of each part of the test set-up accompanied by the reference number (e.g. hydraulic jack (4)) in Fig. 1 is done in the following paragraphs.

As presented in Fig. 1, the experimental set-ups were composed by a three-dimensional restraining frame of variable stiffness (1) used for simulating the restraining to thermal elongation of the column (2) when inserted in a real building structure. This restraining frame was composed by HEB300 beams and HEB400 columns of S355 steel class profiles. The upper beams of the restraining frame were connected to the respective columns by steel threaded rods of steel class 10.9. The different stiffness values obtained for the restraining frame could be achieved by positioning its columns at different positions (Fig. 2). The tested stiffness was obtained with the four columns placed at the end of the beams, reaching the maximum span between opposing columns (Figs. 1 and 2a).

Although different stiffness values were considered in other studies, such as in Correia et al. [7, 10], in this research was considered the axial stiffness of 30 kN/mm corresponding to a rotational stiffness of 94,615 kNm/rad. These are realistic values that reproduce for example one storey building of 3 × 4 bays of 6 m span.

These stiffness values resulting from mounting the columns of the three-dimensional restraining frame in the furthest position. This was decided mainly due to operational requirements of the tests, in order to provide the necessary space for building the adjacent side walls to the testing columns. Another reason for choosing this stiffness was to avoid the development of high restraining forces in the testing columns that could endanger and at the same time shorten the test and thus preventing the observation of the wall's effect on the heating of the columns.

A reaction frame (3) was used to hang a hydraulic jack (4) that applied the serviceability load on the testing columns. This frame was composed by a HEB 500 columns and a HEB 600 beam of steel class S355. The load was controlled by a 2 MN load cell (5) placed between the head of the piston of the hydraulic jack and the top beams of the three dimensional restraining frame.

A special device (6) was developed to measure the axial restraining forces generated in the testing columns due to the restraining to thermal elongation. The device was composed by a massive steel cylinder, Teflon lined (PTFE), that entered in a stiff hollow steel cylinder with a 2MN load cell inside on it that measured the restraining forces.

For the fire tests on columns embedded on walls (Fig. 1a) an electrical furnace (7) placed at one side of the testing specimen was used to simulate the fire conditions. The furnace was composed by a half module of 0.5 m height and two half modules of 1 m height placed on top of each other thus forming a heating chamber of 0.75 m × 1.5 m × 2.5 m.

For the fire tests on isolated columns (Fig. 1b) the test set-up was practically the same of the previous but in this case without walls attached to the testing column. Thus, it was possible to create a closed heated chamber of 1.5 m × 1.5 m × 2.5 m around the testing column.

The furnace was programmed to follow the ISO 834:1999 [13] standard fire curve on heating the test column (8) in some cases only on one side (column embedded on walls) and in the other cases on all sides (isolated column).

2.2. Specimens and instrumentation

The test columns were made of HEA 220 or HEA 100 steel profiles, S355 steel class, and 2940 mm length. Steel plates of 450 × 450 × 30 mm, S355 steel class, were welded to both ends of the testing column resulting in specimens of 3000 mm tall.

The concrete used on the composite columns was C30/37 class. The longitudinal reinforcement was composed by 4ϕ20 rebars and ϕ8 mm stirrups spaced among them 150 mm, both of steel class B500. The stirrups surrounded completely the rebars and passed through holes created in the column's web. The adopted solution, in the opinion of the authors, is better for fire case instead of stirrups of two branches welded to the steel profile's web. The welding in case of fire heats and loses ductility leading to its premature detachment. Fig. 3 presents the cross-sections of the test specimens.

The temperatures were measured at five cross-sections along the column's length (as presented in Fig. 4a) with at least five type